The comparison of Work Of Breathing methodologies on a patient model

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Abstract- **Pressure volume curves were obtained from a surgical patient during the weaning period to determine the inspiratory Work Of Breathing (WOB). The methodologies of Otis and Campbell were used to derive the work per breath. There were differences recorded by these methods, which are explained with the use of an electrical RLC model of the respiratory system.**

The patient was spontaneously breathing during the ventilated support period and then breathing through the ET tube during an unsupported stage, just prior to extubation. The inspiratory work derived from: the airway pressures (Wpaw) were 0.23 ±0.03 Joules per breath (Jpb) and 0.00 Jpb; transpulmonary pressures were 0.31 ± 0.04 Jpb and 0.27 ±0.08 Jpb; Campbell Diagram were 0.30 ±0.06 Jpm and 0.42 ±0.14 Jpb; and a simplified Campbell's method (WcampR0) were 0.24 ±0.05 Jpb and 0.33 ±0.13 Jpb, during supported and unsupported periods, respectively.

The simplistic approach of Wpaw and WcampR0 methods produced work levels that were significantly lower than their standard methods during both phases (p < 0.001). Otis methods show a decrease in the levels of work when the work should have increased due to imposed WOB during the unsupported period, as recorded by using Campbell's methods.

Keywords - Work of breathing, Campbell Diagram, Respiratory model.

I. INTRODUCTION

A Work Of Breathing (WOB) monitor was developed to monitor the mechanics of breathing for ventilated patients in ICU. Pressure volume (P-V) curves were obtained from an intubated post-operative cardiac surgical patient during their weaning period to determine the inspiratory WOB. P-V curves and the methodologies of Otis and Campbell were used to derive the work per breath.

An electrical RLC model of the respiratory system identifies the measuring points of the methods that explain the differences in the derived work values.

II. METHODOLOGY

The Otis methods [1, 2] use either airway pressures (Paw) or transpulmonary pressures (Ppulm) in the P-V curves. Whereas Campbell [3, 4] used oesophageal pressures (Poes) with respect to lung and chest wall static relaxation pressure (compliance) curves.

Otis developed the P-V diagram by defining the areas in the pressure volume relationship of the respiratory system during one breathing cycle at various lung volumes. The Otis diagram plots the breath's tidal volume against pressure and an example of this is shown in Fig. 1 where the plot is partitioned into three areas:

(1) the negative pressure area representing the area in which the expiratory muscles do positive work.

(2) the elastic area bound by the zero pressure baseline and the compliance curve of the total respiratory system (black diagonal line). The elastic work, of that particular, breath is the area within the elastic area, which is limited to the minimum and maximum points of the loop; and

(3) the resistive area of the Otis Diagram where a curve within this area represents the work done to overcome the flow resistance of the respiratory system.

The Otis direct method of determining Work (Wpaw) was to use Paw, refer to (1) on the next page and the more involved method was the use of transpulmonary pressures (Paw-Poes), Wpulm as in (2) on the next page.

Campbell's method of determining the WOB is known as the Campbell Diagram [3]. The Campbell Diagram plots Poes along side the compliance curves of both the lungs and the chest wall. The Campbell Diagram for a single spontaneous breath is shown in Fig. 2. The compliance curve of the lungs is to the left of diagram (the line dissecting the loop on the left) and the chest wall compliance curve is on the right.

Campbell identified the inspiratory work done to overcome the elastic and resistive components of both the lungs and the chest wall. He used the diagram to identify the components by the positioning of the loops with respect to the static
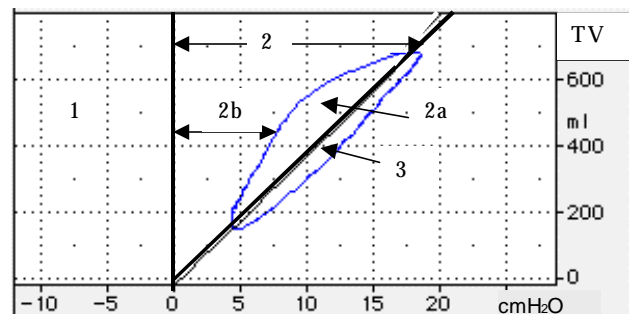

Fig. 1. Otis Diagram during the supported period where the P-V loop starts at 5 cmH$_2$O (CPAP level) and follow the relaxation pressure curve of the total respiratory system (black diagonal line). (1) Expiratory muscle work area. (2) Elastic work areas. (2a) Expiratory flow resistive area. (2b) Negative work area. (3) Inspiratory flow resistive area (TV=Tidal Volume).

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Abstract

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relaxation pressures and in which areas the loops overlapped. The Poes is represented by the wider loop on the left and the derived chest wall pressures (Pw), which is 75% of the lung flow curve of a single breath is the loop on the right [5].

The areas within and between the loops represent the work done to overcome: the flow resistance of the lungs; plus the elastic resistance of the lung; plus the flow resistance of the chest wall. These are the areas that are summed to derive the inspiratory WOB. The oesophageal pressure was normalized so that the breaths start at 0 cmH$_2$O. From these the compliance curves of the lungs and chest wall can be partitioned into three areas on the Campbell Diagram by the "V" shaped compliance curves. Any pressure volume curves plotted on either side of the 'V' area represent the resistive components of WOB. This resistance is the product of the lungs if it is to the left of the 'V' and the resistance is the product of the chest wall if it is on the right of the 'V'. The area within the arms of the 'V' represents the elastic component of inspiratory work. The total sum of these areas is Campbell's inspiratory work, Wcamp as in (3)

When the patient is spontaneously breathing with airway support pressure, a static elastic workload can be introduced by the miss-match in the level of CPAP and Poes. This pressure difference is the result of intrinsic PEEP [6, 7]. The (Pomax-CPAP) component of (3) and (4) accounts for this static elastic work and the normalization of Poes. Equation (4) is the simplest form of the Campbell method where it does not include the chest wall resistance (WcampR0).

The monitoring system comprised of Hewlett Packard (Palo Alto, CA) HP 270 Pressure transducers, HP 8805 amplifiers and the waveforms were digitized by MacADIOS-8ain converter (GW Instruments Inc, Somerville, MA) connected to an Apple Macintosh SE30.

Paw, Poes and flow (Hamilton pneumotachometer connected proximal to the ET tube) were recorded from a 68 year old female patient, spontaneously breathing with 5 cmH$_2$O CPAP and pressure support ventilation (PSV) of 8 cmH$_2$O during the ventilated support period. A relative stable period was selected (Respiratory Rate variation within 1 bpm and Tidal Volume within 40 ml, refer to Table I (n=271)) to recalculate WOB using the four methods. Then P-V loops were recorded during a short period while the patient was breathing through the ET tube without ventilator supported, just prior to extubation.

A paired t-test analysis, with confidence interval of 95%, was used to test the significance between the methods. The accepted level of significance was p<0.05. All statistical analysis were conducted on StatView™ V4.5 (Abacus Concepts, Inc., Berkeley, CA).

$$Wpaw = k\left(\int_{Ti}^{Te}|Paw * Vi|dt\right) \quad (1)$$

$$Wpulm = k\left(\int_{Ti}^{Te}|(Paw - Poes) * Vi|dt\right) \quad (2)$$

$$Wcamp = k\left(\int_{Ti}^{Te}|Poes * Vi|dt + \int_{Ti}^{Te}|Pw * Vi|dt + \int_{Ti}^{Te}|Po\max - CPAP| * Vidt\right) \quad (3)$$

$$WcampR0 = k\left(\int_{Ti}^{Te}|Poes * Vi|dt + \int_{Ti}^{Te}|Po\max - CPAP| * Vidt\right) \quad (4)$$

where k = 0.098 to convert to SI units,
Te = start time for expiration,
Ti = start time for inspiration
Vi = inspiratory volume
Poes = oesophageal pressures
Paw = airway pressures
Pw = chest wall pressures
Pomax = maximum oesophageal pressure
CPAP = level of CPAP

III. RESULTS

The patient's respiratory rate and tidal volumes for both supported and unsupported periods are listed in Table I. Their inspiratory work in Joules per breath (Jpb), derived from the Paw (Wpaw), Ppulm (Wpulm), Campbell Diagram (Wcamp) and a simplified Campbell's method (WcampR0) are also listed Table I.

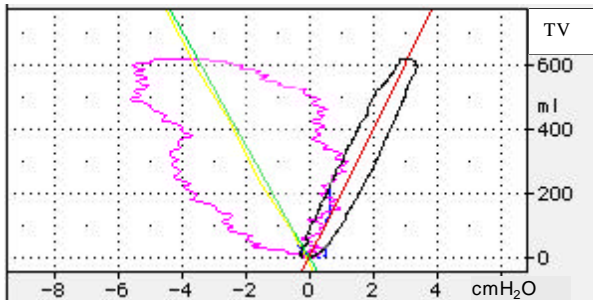Work derived from Otis (Wpaw) and Campbell (WcampR0) methods produce levels that are significantly

Fig. 2. The Campbell Diagrams of one spontaneous breath where the oesophageal pressure loop starts at the zero baseline, travels in a clockwise direction following the lungs' static relaxation pressure (left) line during inspiration. The right loop represents the derived pressure applied by the chest wall.

TABLE I
MEAN (±SD) OF RESPIRATORY RATE, TIDAL VOLUMES AND WORK

	Supported	Unsupported
Respiratory Rate (bpm)	19.4 ± 0.5	21.9 ± 1.9
Tidal Volume (liters)	0.45 ± 0.04	0.48 ± 0.04
Wpaw (Jpb)	0.23 ± 0.03	0.00
Wpulm (Jpb)	0.31 ± 0.04	0.27 ± 0.08
Wcamp (Jpb)	0.30 ± 0.06	0.42 ± 0.14
WcampR0 (Jpb)	0.24 ± 0.05	0.33 ± 0.13

lower than work derived from the other methods during the supported phase ($p < 0.001$). Otis methods showed decreased levels of work when the work should have increased due to imposed WOB during the unsupported period. This increase was recorded by both Campbell methods with the simpler method being significantly lower ($p < 0.001$).

IV. DISCUSSION

The lower values derived by using the simple methods of both Otis and Campbell during the supported period can be defined on an electrical RLC model of the respiratory system, as shown in fig 3. The resistance R, the inductance L and the capacitance C represent flow resistance, inertia and compliance of the system [5]. While the patient is spontaneously breathing and being supported by the ventilator the model has two power sources labeled Vent and Muscle. The location of the "Work" meters shown on the model is determined by the method used. During PSV the Wpaw meter measures the workload imposed on the ventilator by the respiratory system (Wrs). The patient is also spontaneously breathing thus Wpaw will measure the imposed work of the breathing circuit. The Ventilator's pressure support has accounted for the imposed work therefore Wpaw is a measure of Wrs. But the respiratory muscles undertake some of this inspiratory work thus
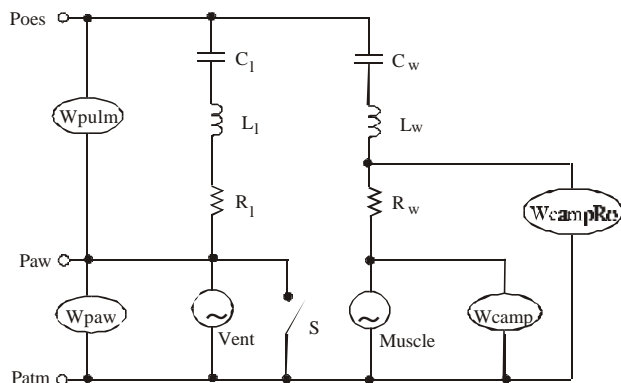

Fig 3: Analogous RLC circuit diagram of the respiratory system which consists of resistive (R), inductive (L) and capacitative (C) elements of the lungs (l) and chest wall (w). Note that R_I represents the resistance of the lung and ET tube. The pressure points represent the airway pressure (Paw) and the oesophageal pressure (Poes) with common representing atmospheric pressure (Patm),. The respiratory muscle activities are represented by the generator labeled Muscle and the ventilator is labeled Vent. Wpaw, Wpulm, Wcamp and WcampR0 meters illustrate the measuring points which are dependent on the method utilised to determine the WOB.

lowering Wpaw. The WcampR0 meter measures the work done on the lungs and the elastic work on the chest wall minus the work done by the ventilator with respect to the patient spontaneously breathing. The assumption made here is that the Muscle source in fig 3 is the dominant power source when measurements are made with the WcampR0 and Wcamp meters. Note that all the meters in fig 3 have their flow sourced from the Paw point of the circuit.

The work derived by Wpulm and Wcamp are significantly higher and reflect the actual work done. As their meters on the model indicate that Wpulm directly measures the work done on the lungs and Wcamp measures the load of the respiratory system and the vent source. Therefore

Wcamp = Wpulm +(work on chest wall) - Wpaw

Otis methods recorded a decrease in work levels when the patient was unsupported. The unsupported period can be shown by closing switch S in fig. 3. This shorts the Vent source (Wpaw = 0) and the model no longer has two power sources. The decrease in Wpulm can be attributed to the extra work required to trigger the ventilator during the supported period and to the pressure support work delivered by the ventilator to overcome breathing circuit resistance.

The advantage of the Otis direct method is that it is not dependent on oesophageal pressures. The P-V loop in the diagram is basically fixed in its axis whereas the Campbell Diagram's loop is dynamic and changes along its axis as the ventilator's level of support changes. The Campbell methods derived an increase in work levels as the respiratory muscles have taken up the load of the respiratory system and the imposed work of the ET tube during the unsupported period [8]. The fact that WcampR0 has a highly significant lower value would argue that the chest wall flow resistance must be account for when deriving the WOB. The Campbell Diagram also partitions the work into its lung and chest wall components thus calculating WOB values that are specific.

Monitoring the one patient during a long stable period recorded P-V curves that had very little variations over a period of time. Therefore any differences in the comparisons of the derived data are solely due to the methodologies used. The RLC diagram models the respiratory system of all patients (without respiratory diseases) and shows that the measuring points with respect to the respiratory system are dependent on method. These measuring points are consistent for all patients, which suggests that other patients are expected to give similar results.

V. CONCLUSION

The work values were compared to reveal that the Campbell Diagram was the method that derived work values, which responded appropriately to the change in power sources during the two periods. The RLC model defined the measuring points of each method and showed that the Campbell Diagram measures the work of the respiratory muscle power source which is dependent on the load of the whole respiratory circuit.

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